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DNS/LES FOR NASA AERODYNAMIC NEEDS AND ENGINEERING APPLICATIONS

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1. Introduction

While both direct numerical simulation (DNS) and large eddy simulation (LES) are at or near the top of a hierarchy of solution methods for turbulent flow fields, the Reynolds number constraints and extensive computational requirements preclude their widespread use as a practical tool in aerodynamic applications. Nevertheless, these methodologies can be used in support of more practical engineering tools such as Reynolds-averaged Navier-Stokes (RANS) formulations.

Aerodynamic flow fields present several challenges even for the most robust RANS approaches. Geometric complexity, Mach number effects, and Reynolds numbers of $\mathcal{O}(10^7)$ contribute significantly to the stringent requirements needed for successful flow field computations. Nevertheless, even with this apparent disparity between the capabilities of DNS and LES and the requirements for accurate prediction of relevant aerodynamic flow fields, both types of simulations can provide useful information if properly chosen "unit problems" are studied. Two examples of practical aerodynamic flow fields will serve to highlight some of the critical dynamical problems as well as the need for well chosen simulations that can help improve the predictive capability of RANS calculations or composite solution approaches.

The inability of RANS formulations to correctly predict critical dynamic features of complex flow fields lies with inadequacy of the closure models for the higher-order correlations that appear in the RANS formulation. A detailed discussion of such closures is outside the scope of the current topic; however, correlations involving the pressure-strain rate or pressure velocity, triple-velocity and (tensor) dissipation rate all can contribute significantly to the predictive accuracy of a RANS formulation. Since experimental stud-

ies are unable, in general, to accurately measure these higher-order correlations, numerical simulations that can help delineate the role of such terms in complex flows is extremely useful.

Ever increasing computational power as well as improved understanding of the effect of filter cut-off on subgrid scale models will continue to move LES (and DNS) towards the realm of an engineering tool. In addition, extensions of RANS formulations to unsteady RANS and related methodologies will continue to move these type of formulations closer toward the realm of a large-eddy solution technique. The future of obtaining such composite formulations will depend on the inherent consistency between the (velocity) fields computed. An example of such a consistency requirement will be discussed here and its effect on model development.

2. Airframe Dynamics

High-lift devices composed of multi-element airfoils (Fig. 1) generate complex aerodynamic flow fields. At cruise conditions, these flows are generally at the high subsonic speed range although conditions can exist in some regions for shocks to develop. Each element of the multi-element system has characteristic features which are of interest in their own right (Rumsey *et al.*, 1998).

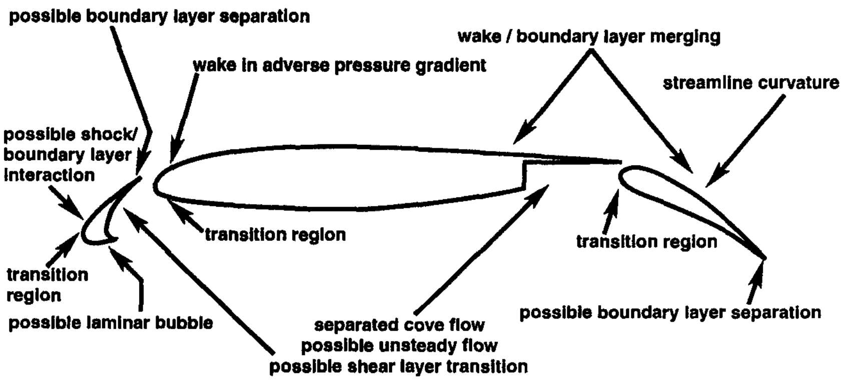

Figure 1. Sketch of multi-element airfoil configuration and important dynamic characteristics (C. L. Rumsey, private communication)

Common to all elements is the need for accurate (natural) transition prediction. Within a RANS formulation, the turbulence closure models need to be properly sensitized to the transition process. Corresponding to the usual practice of turbulence model calibration using both DNS and LES results, can such simulations be performed on (natural) transitioning flows with the goal of providing the information needed for calibration of RANS

closure models? Simulations of transitional flows have been undertaken previously; however, the motivation was not to develop a data base for model development but was to obtain a detailed description of the (nonlinear) stability process leading to a turbulent flow. As such, parameter ranges and dynamics studied did not focus on the data needed to help refine models for disturbance stress fields which would be suitable for RANS-type closures.

Another feature of this multi-element system is that all the elements are dynamically coupled through the interaction of a wake(s) generated by an upstream element and the boundary layer of a downstream element. It has not been possible to accurately predict the downstream evolution of these generated wakes and as such, the downstream predictions have not been accurate as well (Rumsey and Gatski, 2002). It is not clear whether the closure model deficiencies are due to the strong pressure gradients imposed on these wakes (such as the slot generated wake), or the sequence of pressure-gradients the developing wakes experience as they evolve downstream. In isolation, prediction of the near-wake flow field has been successful, at least over a limited range of pressure gradients (Carlson *et al.*, 2000). While DNS of a wake flow has been performed previously (Moser *et al.*, 1998), it did not focus on effects of pressure gradient or other issues related to the multi-element dynamics of interest here. Nevertheless, a well-posed and accurate DNS (or LES) could be used to validate the predictive capability of a RANS model for such wakes in relative isolation to other complicating dynamic features associated with the full configuration.

In addition to transition location and wake evolution which affect the global behavior of the multi-element flow field, each element of the system also has some characterizing dynamic features. The slat, for example, is composed of a curved, transitional flow which can sustain shocks depending on configuration, and a possible unsteady, transitioning shear flow in the lower surface cove region. Thus, shock boundary-layer interaction prediction on the curved upper surface can be an important feature of any overall prediction scheme of high-lift dynamics. Unfortunately, the ability to accurately predict such shock-boundary layer interactions are strongly problem dependent. On the lower surface of the slat experiments have shown an inherent unsteadiness in the flow. Unfortunately, such measurements are difficult and detailed mappings are unavailable. In any case, such unsteady effects produce a significant challenge to any prediction scheme. Well-focused simulations of model flows which can partially capture some of these key features of the practical configuration can be critical to identifying specific deficiencies of a particular RANS closure scheme.

The main element has been less problematic once the transition location is properly predicted or fixed. Errors in the slat wake predictions inherently persist downstream; however, the slat wake velocity deficit only begins to

interact with the main element boundary layer near the aft portion of the element. In addition, the flow over the flap is moderately curved which further complicates the dynamics. Turbulence models currently available are only moderately successful in capturing all these dynamics, even in well-posed comparative studies with experiments. Clearly, a significant challenge is to identify suitable test flow fields that can be accurately computed with DNS or LES approaches, and still provide a database that can be used to validate turbulent closure models that could lead to improved closures.

The mean velocity field over the flap is characterized by a velocity deficit produced by the merging of the slat wake with the main element boundary-layer flow and an altered inner layer velocity field due to the gap between the main element and flap. As the angle-of-attack increases, flow separation over the high-lift device may be initiated over the flap adding to the complexity of the flow. Obviously, prediction schemes are not successful over a wide parameter range and could benefit from simulations which isolate key features. One area of particular interest would be the flow field dynamics in the region downstream of the separation point. A detailed mapping of this flow would hopefully allow for improved model development.

3. Engine Flow Fields

A second example of a complex aerodynamic flow field is that associated with scramjet/ramjet engines (Fig. 2). The inlet flow field is composed of complex shock boundary-layer interactions and the detailed dynamics of such flows is not well understood. Downstream in the combustor, high speed fuel injection occurs resulting in a complex mixing process with shocks present.

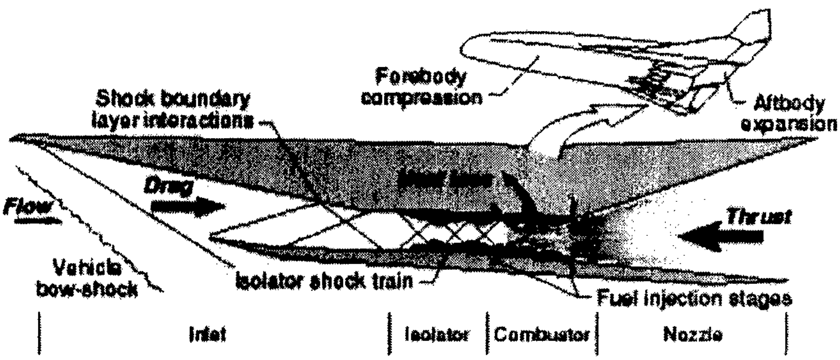

Figure 2. Sketch of inlet flow field of scramjet/ramjet engine and important dynamic characteristics (J. A. White, private communication)

Once again, such flow field predictions are beyond the capabilities of ei-

ther direct or large-eddy simulations. Thus, at this time a RANS approach is the only practical means of obtaining predictions of the flow field. The challenge, then, is to identify important dynamical features which characterize different regions of the flow field and formulate suitable DNS and LES unit problems that can be studied to improve the RANS closure models. Compressible RANS approaches using Favre-averaged variables have been the methodology most commonly used in such flows. Such approaches yield additional correlations in the governing equations which are due to compressibility and for which closure models need to be developed. These may include heat and mass flux models as well as dilatation models. Depending on the degree of compressibility, the turbulence can be significantly altered from its incompressible behavior. If so, several modeling issues arise which, unlike the incompressible case, need to be resolved. While numerical simulations have been performed in the last decade on compressible flow fields (e.g. Freund *et al.* 2000, Sarkar and Pantano 1999), the results have not been extensively utilized in model development. Thus, at the outset it would be beneficial to examine simulations already performed and evaluate their usefulness on improving existing currently available models.

As Fig. 2 shows, the inlet region is dominated by a complex shock pattern which has a significant impact on the flow field. Useful information could be obtained from a simple boundary-layer computation with an impinging shock (e.g. Adams 2000). Such a calculation would give some insight into the dominant dynamic features that would need to be considered in the full problem. Another important feature of such flows is the high-speed fuel injection process. The injection produces a very complex flow field which is very challenging to predict. Can a representative DNS or LES unit problem be devised that would successfully replicate some of the important physics? Such a database could be used to validate existing models or lead to the development of improved closure models.

Certainly complex flow field dynamics are not limited to the scramjet/ramjet engines. Unlike the scramjet/ramjet engines, turbofan engines contain a rotor/stator assembly which introduces extra strain effects into the turbulent flow field. Flow curvature and non-inertial effects adds to an already complex flow that includes leading-edge shocks ahead of the rotor blades, shedding vortices, and unsteady wakes.

4. Future Challenges

Many new challenging problems continue to arise predicated on the need to better control the flow field dynamics in complex configurations. Adaptive flow and noise control are but two examples along with the continuing need to improve the predictions of the type of flow fields discussed in the previous

sections.

Adaptive or active flow control comprise a closed system where a continuous feedback loop exists to optimize some flow field characteristic. Active cavity, fluid/structural shaping and separation are examples of control mechanisms that can be used. Each of these control mechanisms when embedded in complex aerodynamic configurations would require highly resolved simulations in order to adequately describe the complex flow field dynamics. The same holds true for improved airframe, fan and jet noise control. Detailed simulations of full configuration slat leading edge, flap trailing and side-edge, and/or landing gear geometries are prohibitive.

As in the previous sections, DNS and LES methodologies may be best suited to problems that describe the complex flow field structure in simplified geometries but which still capture the key dynamic features of the full flow field. Another approach would be to develop composite methodologies capable of achieving the accuracy of the DNS and LES methodologies, but in full configurations. Such composite or hybrid approaches have begun to be formulated and these include the Detached Eddy Simulation (DES) (e.g. Spalart 1999) and the Flow Simulation Methodology (FSM) (e.g. Zhang *et al.* 2000).

Such composite approaches can be constructed from modified Reynolds averaged Navier-Stokes (RANS) and LES formulations, for example. The usual RANS-type formulations are probably unacceptable since they do not in general handle non-equilibrium effects properly and are not properly sensitized to the broad spectrum of scales present. Extensions to the usual RANS-type formulations include, for example, the triple-decomposition approach originally proposed by Reynolds and Hussain (1972) and the Semi-Deterministic Method (SDM) (Ha Minh and Kourta 1993). Such extensions inherently solve time-dependent RANS-type formulations and as such have been referred to as unsteady RANS (URANS), time-dependent RANS (T-RANS) and VLES. The label VLES (Very Large Eddy Simulation) of course being put forward to establish a formal link with the LES approach. Some new alternatives to LES are now also appearing such as the Navier-Stokes-α model which includes nonlinear dispersive effects (Chen *et al.* 2000), and the Coherent Vortex Simulation (CVS) approach (Farge *et al.* 2000, see also Goldstein *et al.* 2000). It remains to be seen whether such approaches provide better modeling insight for RANS-type closures or a more conducive basis for composite formulations.

It should be recognized that while the RANS and LES equations are formally equivalent, the flow field is being described differently due to the disparity of scales being resolved. Thus, one might naturally ask whether there is some way in which both methods would produce the same flow field as described by the velocity field, for example.

It is worthwhile to look at a strategy proposed by Germano (1999). Consider the ensemble mean of both the velocity and pressure fields and assume that for $f(\mathbf{x},t)$ ($u_i(\mathbf{x},t)$ or $p(\mathbf{x},t)$)

$$E\{\underbrace{f(\mathbf{x},t)}_{\text{DNS}}\} = E\{\underbrace{\overline{f}(\mathbf{x},t)}_{\text{LES}}\} = \underbrace{F(\mathbf{x},t)}_{\text{ANS}} \tag{1}$$

The ambiguity associated with averaged Navier-Stokes variable is intentional. In both DNS and LES, the statistical average of the variable (DNS) or the filtered variable (LES) is performed simultaneously with (or post-processed after) the numerical solution of the Navier-Stokes equations. In RANS-type formulations (which are labeled here as ANS for Averaged Navier-Stokes), it is the averaged variable which is solved for directly. For this reason, the ANS mean velocity and pressure will simply be represented by U_i and P, respectively.

Now, in addition to Eq. (1) which assumes the equivalence of the ensemble mean of the filtered quantity with the ensemble mean, it is also required that the corresponding mean momentum equations be equivalent, then

$$\left(\frac{D}{Dt} - \nu\frac{\partial^2}{\partial x_j \partial x_j}\right) E\{u_i\} + \frac{\partial}{\partial x_i}E\{p\} = \mathcal{S}_{\text{DNS}} \tag{2}$$

$$\left(\frac{D}{Dt} - \nu\frac{\partial^2}{\partial x_j \partial x_j}\right) E\{\overline{u}_i\} + \frac{\partial}{\partial x_i}E\{\overline{p}\} = \mathcal{S}_{\text{LES}} \tag{3}$$

$$\left(\frac{D}{Dt} - \nu\frac{\partial^2}{\partial x_j \partial x_j}\right) U_i + \frac{\partial}{\partial x_i}P = \mathcal{S}_{\text{ANS}} \tag{4}$$

where

$$\frac{D}{Dt} = \frac{\partial}{\partial t} + E\{u_j\}\frac{\partial}{\partial x_j} = \frac{\partial}{\partial t} + E\{\overline{u}_j\}\frac{\partial}{\partial x_j} = \frac{\partial}{\partial t} + U_j\frac{\partial}{\partial x_j}, \tag{5}$$

and

$$\mathcal{S}_{\text{DNS}} = -\frac{\partial}{\partial x_j}E\{(u_i - E\{u_i\})\,(u_j - E\{u_j\})\} \tag{6}$$

$$\begin{aligned} \mathcal{S}_{\text{LES}} &= -\frac{\partial}{\partial x_j}\left(E\{\overline{u_i u_j}\} - E\{\overline{u}_i\}E\{\overline{u}_j\}\right) \\ &= -\frac{\partial}{\partial x_j}\left[E\{\left(\overline{u}_i - E\{\overline{u}_i\}\right)\left(\overline{u}_j - E\{\overline{u}_j\}\right)\} + E\{\tau_{ij}^{\text{SGS}}\}\right] \end{aligned} \tag{7}$$

$$\mathcal{S}_{\text{ANS}} = -\frac{\partial}{\partial x_j}\tau_{ij} \tag{8}$$

Note that here the second-moment of the fluctuating velocity τ_{ij} is given by some statistical average of $(u_i - U_i)(u_j - U_j)$.

The partitioning suggested by $\mathcal{S}_{\rm LES}$ can also be clearly shown in spectral space. For a statistically homogeneous field using a sharp cut-off filter $(\hat{G}(\mathbf{k}) = \mathcal{H}(k_c - |k|))$

$$
\begin{aligned}
E\{\left(\overline{u}_i - E\{\overline{u}_i\}\right)\left(\overline{u}_j - E\{\overline{u}_j\}\right)\} &= \int_{\forall k} d^3\mathbf{k}\ \hat{G}^2(\mathbf{k})\Phi_{ij}(\mathbf{k},t) \\
&= \int_{|k|\leq k_c} d^3\mathbf{k}\ \Phi_{ij}(\mathbf{k},t) \qquad (9)
\end{aligned}
$$

and

$$
\begin{aligned}
E\{\overline{u_i u_j} - \overline{u}_i\overline{u}_j\} = E\{\tau_{ij}^{\rm SGS}\} &= \int_{\forall k} d^3\mathbf{k}\ (1-\hat{G}(\mathbf{k}))^2\Phi_{ij}(\mathbf{k},t) \\
&= \int_{|k|\geq k_c} d^3\mathbf{k}\ \Phi_{ij}(\mathbf{k},t) \qquad (10)
\end{aligned}
$$

where the energy spectrum tensor $\Phi_{ij}(\mathbf{k},t)$ is related to the Fourier transformed instantaneous velocity $\hat{u}_i$ by

$$
E\{(\hat{u}_i - E\{\hat{u}_i\})(\hat{u}_j - E\{\hat{u}_j\})\} = \delta^3(\mathbf{k}+\mathbf{k}')\Phi_{ij}(\mathbf{k},t) \qquad (11)
$$

Equations (9) and (10) show that as the cut-off wavenumber increases, the contribution from $\tau_{ij}^{\rm SGS}$ diminishes and the LES formulation evolves toward a full DNS; whereas, as the cut-off wavenumber decreases, the contribution from $\tau_{ij}^{\rm SGS}$ increases and more of spectrum needs to be modeled.

In order that the velocity fields $E\{\overline{u}_i\}$ and U_i computed from either an LES Eq. (3) or a RANS-type Eq. (4) formulation be the same, a formal requirement for consistency between the two methodologies would be

$$
\tau_{ij} = E\{\left(\overline{u}_i - E\{\overline{u}_i\}\right)\left(\overline{u}_j - E\{\overline{u}_j\}\right)\} + E\{\tau_{ij}^{\rm SGS}\}, \qquad (12)
$$

or using Eqs. (9) and (10),

$$
\int_{\forall k} d^3\mathbf{k}\ \Phi_{ij}(\mathbf{k},t) = \int_{|k|\leq k_c} d^3\mathbf{k}\Phi_{ij}(\mathbf{k},t) + \int_{|k|\geq k_c} d^3\mathbf{k}\Phi_{ij}(\mathbf{k},t). \qquad (13)
$$

The relation in (12) can also be shown to be a direct consequence (Germano 1999) of the initial assumption about the mean fields in Eq. (1). Germano (1999) used the result in Eq. (12) to derive a simple relation for the subgrid scale eddy viscosity. An alternative view would be to use (12) as a guide to improved modeling of τ_{ij}.

In a statistically steady flow, where the ANS is simply the usual RANS (e.g. long time average) formulation, τ_{ij} contains the entire effect of the

turbulence on the mean flow, and in a sense corresponds to the limiting value for a decreasing cut-off wavenumber k_c. However, in statistically unsteady flows where methods such as unsteady RANS (URANS or T-RANS, VLES) may be needed, contributions from both Eqs. (9) and (10) need to be properly represented by τ_{ij} in order for consistency with an LES formulation. In practice, for inhomogeneous flows the mean (velocity) fields obtained from a RANS-type formulation are associated with temporal averages. This further complicates any consistency arguments due to the fact that any coupling between such a temporal average and the spatial filtering associated with an LES would necessarily involve a complicated (and probably unknown) dispersion relation (Pruett, 2000) that needs to be taken into account.

5. Summary

While direct and/or large eddy simulations are probably not going to be capable of predicting complex aerodynamic flow field themselves, the methodologies can and should be utilized to solve flow problems that replicate the essential dynamic features of the full problem. In the near term, this may be the most useful role of such methodologies rather than as a substitute to the currently available RANS-type models. These simulation results can then be used to develop improved closure models for higher-order correlations that appear in the models for the Reynolds stress tensor.

Within this framework, examples of complex aerodynamic flow fields including a high-lift system composed of a multi-element airfoil configuration and a scramjet/ramjet engine configuration were used to highlight the need for well chosen unit problems that would isolate the key dynamics associated with such flows.

Currently, composite methodologies are appearing which attempt to utilize both the LES and RANS-type formulations. Formal and complete methods which correctly utilize these two formulations may need to satisfy some consistency requirements in order to insure that both the LES and RANS-type formulation will yield the same mean flow fields.

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